Full-scale measurement and analysis of train slipstreams and wakes. Part 2 Gust analysis

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Full scale measurement and analysis of train slipstreams and wakes: Part 2 Gust analysis

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Abstract

Part 1 of this paper reports results from the extensive full scale slipstream measurements carried out as part of the AeroTRAIN project, and in particular concentrates on the ensemble analysis of this data. This paper concentrates on the analysis of maximum gusts, in order to make suggestions for modifications to the current TSI methodology. The very large dataset obtained for one particular high-speed train type (the S-103) enabled the variation of slipstream gusts with vehicle speed and wind speed to be determined. It was also possible to carry out a statistical analysis of the gusts that enabled the standard uncertainty of the TSI gust parameter to be determined. It was shown that for most trains the maximum gusts occurred in the train near wake, but for double unit trains the maximum gusts could occur around the gap between the units and for locomotive / coach combinations the maxima could occur around the nose of the locomotive or at the discontinuity between the train and the locomotive. Perhaps the most significant result, which could allow a considerable simplification of the TSI methodology, was that if both trackside and platform measurements for a particular train were plotted against height above the rail, then, with very few exceptions, they fell onto one curve, which implies that a trackside measurement could replace the current required platform measurement.

Notation

U(peak)	Peak value of horizontal slipstream velocity, normalised by train speed
U(TSI)	Horizontal slipstream velocity obtained using TSI methodology, normalised by train speed.
x	Distance along the track (measured from vehicle front)
y	Distance normal to the track (measured from the centre of the track)
z	Distance in the vertical direction (measured upwards from the top of the rail)

1. Introduction

This paper is the second part of a two part paper that presents and discusses the results of a major series of experiments to measure the slipstream velocities of trains of different types. These tests were carried out as part of the AeroTRAIN project in order to develop a revised methodology for the CEN code [1] and the TSI provisions [2] for the assessment of train slipstreams. The current methodology for assessing the magnitude of the slipstreams of a train requires that full scale measurements be made at specific points on a platform and at the trackside for 20 train passes, with a defined vehicle speed range and for low wind conditions. The maximum one second moving average velocity for each train pass is then calculated. A value of the mean plus two standard deviations of the ensemble is then compared with a limiting value specified by the TSI. The need for two measurement locations, one at trackside and one on a platform of a specific height, makes this type of testing somewhat cumbersome, particularly accessing the required platform test site. A method based on one set of measurements at the trackside that is transferable to any country would be rather more convenient and cost-effective. For this reason, one work package of AeroTRAIN project was devoted to looking at the testing procedure for slipstream measurements, with a view to reducing the number of measurement locations. Note that in what follows all the gust values presented are effectively one second average gusts. It is acknowledged that this is an arbitrary figure that does not fully relate to human behaviour in wind gusts [3], but because it is used in the TSI methodology, this value will be retained here.

In part 1 of this paper, the AeroTRAIN experiments were described, together with the results from two earlier investigations that were also used in the analysis. These experiments are summarised in table 1, taken directly from Part 1 but included here for convenience. These were carried out at three measurement sites as follows.

- Tests in Spain on both tracks of the Madrid / Barcelona 300 km/h high speed line near Guadalajara – Yebes railway station (denoted in what follows by GY) by Deutsche Bahn (DB) on track 1 (the Barcelona direction) and track 2 (the Madrid direction), and by Bombardier Transportation (BT) on track 1 only.
- Tests in Germany at Westendorf station (denoted by WE), by DB on track 1 and platform 1 (0.18m high) (Donauwörth to Augsburg direction) and the University of Birmingham (UB) on track 2 and platform 2 (0.38m high) (Augsburg to Donauwörth direction).
- Tests in Germany at Kutzenhausen station (denoted by KH) by UB on the 0.38m high platform in the Ulm direction.

Measurements were made for a wide variety of trains, at "trackside" (with this simplified terminology we indicate an open line in specified standard conditions) and above platforms of various heights, with details being given in table 1. Part 1 was primarily concerned with the ensemble averages of the slipstream data and presented results for such ensembles for a wide range of trains with measurements made at trackside and above platforms. The effects of cross winds were also considered. The nature of the flow field around trains was discussed at some length and the following conclusions reached.

- For high speed single unit trains, a distinction can be drawn between trains with rounded noses / tails (such as the S-103) and trains with smaller curvatures around the noses and tails and single wheel axis (such as the S-102). The former tend to show greater boundary layer growth along the side of the train and a less abrupt and distinctive peak in the near wake, than the latter.
- High speed double unit trains show slipstream ensemble peaks just behind the junction between the units and in the near wake of the train.
- Locomotive hauled trains show ensemble peaks around the nose and the discontinuity between the locomotive and the carriages, and in the wake of the train. These peaks at the

discontinuity become larger as the discontinuity becomes more pronounced. Moreover, locomotives in leading and trailing position can be distinguished.

- Very low platforms may result in higher slipstream velocities at the equivalent height above the track than trackside measurements, as highly energetic flows from near ground level are forced onto the platform. Higher platforms tend to confine these flows below platform height.

In this paper we move on from considering slipstream ensembles to considering peak slipstream values, which are of more direct relevance to the CEN / TSI procedure. The methodology for obtaining these values is set out in section 2, and considers the uncertainty associated with forming ensembles of these values as required in the current methodology. Section 3 then considers the measurements of maximum gusts for the trackside measurements and section 4 considers the platform measurements. The effects of vehicle speed and wind speed are considered in section 5 and the results are discussed in section 6. Conclusions are drawn in section 7.

2. The analysis of one second gusts

Table 2 indicates those sets of experimental data for which gust magnitudes were derived, and the number of runs that were used in each case. It can be seen that whilst for some cases, there is a very large number of runs (greater than 300 for the S-103 for example) for others the number of runs is very much smaller, and often well below the value of 20 that is required in the TSI methodology. Now in essence the derivation of one second gust values is straightforward. For each admissible train pass (in terms of vehicle speed and cross wind speed), a running one second average of the slipstream velocity time history is obtained, and the maximum value of the time history recorded, together with its position relative to the train nose. Two points must however be appreciated.

- This averaging procedure results in a gust that is averaged over a significant proportion of the train length – for example, for a 200m high speed train travelling at 80m/s, this represents an average over 80m, which thus results in a very considerable smoothing of the data that can eliminate peaks of short length / duration.
- As with the ensembles, there is considerable scatter in these results, and a proper statistical methodology must be used to understand them.

As an example of this, figure 1 shows the gusts measured for the S-103 at two heights. It can be seen that the maximum gusts cluster in the near wake of the train, with some centred just before the end of the train (note that the points correspond to the centre of the one second averaged gust). These decrease in magnitude with distance downstream as would be expected (trend lines not shown for clarity). The values measured at z=0.2m seem to be, on average, larger than those measured at z=1.2m, but the scatter makes this difficult to judge. In order to understand the nature of these results more fully, probability distributions of the gust magnitudes were obtained. These were divided into three types.

- Type 1 that occur between x=0 and x=200m, i.e. along the length of the train (27 values)
- Type 2 that occur between x=200 and x=600m i.e. in the near wake (255 values)

- Type 3 that occur between x=600 and x=800m i.e. in the far wake (47 values)

The frequency distributions are shown in figure 2, together with the normal distribution for the entire dataset. Statistical analysis shows that all of the distributions can be represented by normal distributions. The three distributions are slightly different: compared with type 2 peaks (near wake), type 1 peaks are characterised by a similar mean and larger standard deviation, while type 3 peaks show a similar standard deviation but lower mean (Figure 3). This conclusion is drawn from statistical significance tests ("F-test") with a confidence level of at least 95%. It applies to both heights above TOR (z=0.2 m and z=1.2 m). It is also evident from Figure 3 that if the values of type 1 and type 2 were from the same population, the near wake region, with over 250 runs, would show at least the same dispersion as the trainside region (less than 30 runs), whereas the dispersion is actually less for the type 2 peaks in spite of the large number of runs.

Now the parameter that is used to describe such distributions in the TSI / CEN methodology is the mean plus two standard deviations of the ensemble of the gust values, with the ensemble length being specified as 20 runs. One might expect this parameter to show some variations between different 20 run ensembles, and that this variation will increase as ensemble length becomes shorter. The very rich S-103 dataset enables this effect to be investigated. Figure 4 shows the variation in the TSI gust parameter for different ensemble lengths. As would be expected the variation in this parameter becomes smaller as ensemble length increases. The uncertainty shown by different 20 run ensembles seems to represent a good balance between practicability and accuracy. As the ensemble length falls below 20 the uncertainty quickly increases since it combines the uncertainty in both the mean and the standard deviation of the ensemble. It is possible to determine, under the assumption of fixed test site, the standard uncertainty for any particular ensemble as a function of number of runs, and the standard deviation / mean ratio. The results are shown in figure 5. For most of the ensembles considered here, the standard deviation / mean ensemble ratio are of the order of 0.2, although some values of this ratio can be significantly higher. Thus a 20 run ensemble formed with data from this specific site will have a standard uncertainty of around ±6% and thus a 95% confidence limit of twice that value.

3. Trackside gusts

In this section we consider the variation of the TSI gust parameter *U(TSI)* for different types of train, heights above the track etc. Firstly however, figure 6 shows, for a small number of representative trains, the variation of individual gust magnitude with distance from the train nose. Data is shown for S-100 (representative of single unit high speed trains), ICE-2 (representative of double unit high speed trains), S-120 (representative of shorter high speed units) and S-252 plus coaches (representative of locomotive hauled trains). For the S-100 it can be seen that the peaks cluster in the near wake of the vehicle, which is consistent with the ensemble average results of part 1. For the ICE-2 there are clusters of peaks both around the end of the train, and in the centre of the train close to the coupling link. The latter arise because of the geometric discontinuity between the two units, and are again consistent with the ensemble analysis of Part 1 which shows a double peak for this vehicle. The S-120 results are again clustered in the near wake as would be expected. The results for the S-252 plus coaches however show a very different pattern, with two distinct clusters of peaks – one arising as a result of the nose of the locomotive and the discontinuity between the locomotive and the trailing coaches, and one group in the near wake. Again this is consistent with the ensemble average results.

These four sets of results are representative of the other data from a wide variety of trains, and we thus now consider only the values of *U(TSI)* obtained from these data. These are shown in tables 3 to 6 for the four different categories of train. The tables give results for trackside measurements for a wide range of trains at different heights above the top of the rail. An indication of the 95% confidence limit (obtained from the analysis that led to figure 5 for specific values of the number of train passes and standard deviation / mean ratios) is also given. We consider each of the tables in turn.

Table 3 shows the results for the high speed trains. The gust values are all very similar with normalised values of around 0.15 to 0.25, with a general decrease as the height above the top of the rail increases. This reflects the larger scale unsteadiness caused by the bogies and the underbody equipment. Where nominally identical runs have been carried out (eg. at GY T12 and GY T1) the confidence limits for the *U(TSI)* values usually overlap. The exception to this is for the S-103 at the lowest height and for the S-120 at the middle height (the shortest trainset tested) where the two sets of data are rather different. The reasons for these differences that are not clear. In terms of the effect of different train types, little can be said as most of the results are similar, although the results do suggest that the S-103 produces the lowest values of *U(TSI)* and the ICE-2 gives the highest values. It should again be noted at this point however that the *U(TSI)* values are a combination of the means and standard deviations of the gust ensembles and reflect trends in both these parameters. An more detailed examination of the data reveals that the fall of *U(TSI)* with height is largely due to a fall in the mean values of the ensemble, with no consistent trend in the standard deviations of the ensemble. However for the S-103 results there is a clear trend of the standard deviation increasing with height as the mean falls, with the standard deviation / mean ratio increasing from 0.22 at a height of 0.2m to 0.48 at a height of 1.58m, indicating a much more unsteady flow as the height increases.

Table 4 shows the results for the double unit high speed trains. For these trains the number of train runs was relatively small and thus the uncertainties are high. That being said, the results are similar to those in table 3, although for the S-102 and S-103 double units the *U(TSI)* values are a little higher than for the single unit trains. The ICE-2 results are significantly higher than the other results, an observation which is again consistent with the high levels of the ensembles given in Part 1 of this paper.

Table 5 gives the *U(TSI)* values for short passenger unit trains - the BR440, which is a blunter lower speed commuter vehicle. The normalised gust values are higher than for the high speed single unit vehicles, and again in general decrease with height above the rail. The confidence limits for the results for the two nominally similar datasets overlap.

Finally Table 6 shows the results for a number of locomotive / coach combinations. Again the gust values decrease with height throughout. There is however a considerable train to train variation, with the S-252 plus coaches having the lowest normalised gust values, and the DOSTO with locomotive leading (with a very considerable geometric discontinuity) having the largest values. It is of interest to note that the DOSTO loco trailing configuration has rather lower TSI gust values than the loco leading configuration.

4. Platform gusts

In a similar manner to the last section, the *U(TSI)* values measured above platforms for a range of trains are shown in tables 7 to 10. In broad terms these are similar to the trackside values, with a general decrease with height above the top of the rail. As the number of train passes is less than for the trackside cases, the uncertainties are rather larger than at the trackside. A comparison of the trackside and platform *U(TSI)* values is shown in figure 7 for the trains where comparative data exist. In all cases the values of *U(TSI)* are plotted against height above the track, for both trackside and platform values. These figures show a clear decrease as the height above the track increases, and, interestingly, the platform and trackside data fall in the main on the same curve for any particular type of train, with a considerable overlap of the confidence limit bounds. The major exception to this seems to be for the ICE-2 double unit at WE T1 and WE P1, where the platform values are significantly higher than the trackside values. WE P1 is the lowest of the platforms that was used in the experiments at 0.18m high, and it was argued in part 1 that for this platform the energetic flow low down at trackside is funnelled up onto the platform, resulting in high slipstream velocities.

5. The effects of wind and vehicle speed

Within the TSI methodology there are restrictions on both the vehicle speed and the wind speeds that are allowable before a train pass can be used within the TSI gust calculation – generally between 90 and 100% of the maximum train speed and wind speeds of less than 2m/s over the 3 seconds before the train passes the measurement point, regardless of wind direction. In this section we thus investigate the effect of both parameters on TSI gust velocities using the extensive GY T1 S-103 dataset of 269 individual gust values measured on the same track (T1). Figure 8 shows the variation of gust speed with vehicle speed. It can be seen that there is little discernible trend in the mean of the normalised gust speed as the vehicle speed varies from its maximum value to less than half that value. The TSI methodology thus seems somewhat restrictive in this regard. That being said, there is an indirect effect. All the gust values shown in figure 8 are one second values. Thus the length over which the gusts are averaged will be shorter the lower the train speed. Because of the essentially unsteady nature of the vehicle wake, this might be expected to result in a greater scatter in the data at lower vehicle speeds. This is discernible by taking a closer look at figure 8. There are three main clusters of points at approximately 63 m/s, 80 m/s and 82 m/s. The cluster at the lower speed contains significantly less values (runs) than the other two. Nevertheless, the dispersion of the values (standard deviation of the cluster) is roughly the same as for the other two clusters, indicating that the "low-speed" cluster values proceed from a distribution with a larger standard deviation, thus confirming the intuition based on the physics of the phenomenon. A statistical analysis confirms that it is quite unlikely that the "low-speed" cluster proceeds from the same population as the other two (confidence level >95%). This is an argument for retaining the current TSI speed restriction, in particular as experience would suggest that there are no practical issues in achieving train speeds within the required range.

Now consider the effect of wind on the gust values. In part 1 of this paper, it was shown that the ensemble means of slipstream velocity for the S-103 were sensitive to yaw angle. This is the angle between the vehicle direction of travel and the wind speed relative to the vehicle, and thus takes into account cross wind speed and direction. The ensemble slipstream velocities for negative yaw angles, for which the vehicle wake was convected onto the measurement position, were higher than for positive yaw angles, when the wake was convected away from the measurement probes. A similar trend can be seen in the plot of individual gust velocities in figure 9, which shows the gust variation with yaw angle for the S-103 Velaro at two heights. A best fit line is shown, and although the scatter is considerable there is a clear trend, with the negative yaw values being, on average greater than the positive yaw values. Figure 10 shows a plot of the position at which the gusts occurred relative to the nose of the train, against yaw angle. Again the scatter is considerable, but it is clear that the negative yaw angle peaks occur closer to the train tail than the positive yaw angle peaks – which is consistent with the wake convection direction. Therefore it is clear that the gusts are dependent on yaw angle and thus cross wind conditions, although it is only in a large dataset such as that of the S-103 that such trends would be discernible. Further of course, there is no guarantee that the effects would be similar for other trains.

6. Discussion

In this section we discuss how the gust results presented in this paper relate to the ensemble velocity measurements of Part 1, and also how they relate to the gust limits in the TSI methodology. Recommendations are also made on possible revisions to the TSI methodology.

Figure 1 shows how the position of the maximum gusts varies for the S-103 and figure 6 shows similar results for a variety of other train types. It is clear that, whilst most peaks occur in the near wake just behind the train for most train types, for some runs the maximum gust occurs further along the wake, and not surprisingly the magnitude of these maximum gusts falls off with distance from the train. It is thus clear that the gust magnitudes cannot be statistically stationary with respect to distance along and behind the train, and the TSI methodology, whilst undoubtedly convenient, in allowing the *U(TSI)* values to be determined from gusts at a wide range of positions along the train, cannot be regarded as statistically rigorous. An alternative approach would be to define the gust value as the one second moving average maximum of the curve obtained by taking the mean plus two standard deviations of 20-run ensembles presented in part 1 – which would at least locate the gust value at a consistent point (the peak value thus calculated always falls close to the train end). Table 11 shows the ratio of the *U(TSI)* obtained with the current methodology to the *U(TSI)* based on the alternative ensemble average approach. In general the values are somewhat below unity, due to the fall off of gust values in the vehicle wake, although there are a small number of cases where this is not the case.

Now consider how the current results relate to the TSI limits. In [2] three limit values are prescribed at the TSI measurement positions

- 22m/s at z=0.2m at trackside – at the maximum train speed or 300 km/h whichever is lower for trains with a maximum speed of equal or greater than 250 km/h
- 20m/s at z=0.2m at trackside – at the maximum train speed or 249 km/h whichever is lower for trains with a maximum speed between 190 and 249 km/h

- 15.5m/s at 1.2m above a platform at 200 km/h or maximum train speed whichever is lower.

Table 12 shows, for a number of different types of train and measurement heights, the calculated values of the gust mean, standard deviation and *U(TSI)*, in m/s, for the maximum train speed, together with the appropriate limit value. By assuming that the gust means and standard deviations define a normal distribution the probability of the limits being exceeded in each case can be calculated. These are shown in the table in the form log(1/probability of limit being exceed in any one train pass) i.e. the logarithmic return period for train passes exceeding the limit value. A value of 1.0 thus indicates that the limit will be exceed every 10 runs, a value of 2 every 100 runs etc. It can be seen that for most of the vehicles there is a very low probability of the limit values being exceeded,the lowest being for the S130 where an exceedance would be expected about once every 10,000 train passes. . The table illustrates the approach but as it do not take into account the number of runs from which the distributions are derived the actual values for trains with few runs is at best indicative.

Thus on the basis of the results that have been obtained, in what ways can the current TSI methodology be simplified to make it more straightforward and practical? The following is suggested as a way forward.

- The basic form of the methodology should be retained, but the platform based measurements could be replaced by trackside measurements at a suitable height – say 1.4m above the top of the rail, where for typical platform heights of around 0.3 to 0.5m, the results suggest that the trackside and platform measurements at the same height above the rail are similar when assessment uncertainty is considered. At the lowest platform height tested (180 mm above TOR, 60 mm lower than the value indicated in the RS TSI [2]) the results suggest the possibility of gust speeds that are systematically higher with respect to trackside measurements at corresponding heights, but the differences are again comparable with the estimated assessment uncertainty.

- Make no change to either the vehicle speed restrictions (which present no practical problems) or the wind speed restrictions (which seem to be an appropriate balance between accuracy and practicality).
- Make no change to the formulation of the TSI gust (the mean plus two standard deviations of the maximum one second gust in 20 or more runs/independent measurements), but be aware of the uncertainties associated with such a procedure in the application of the results.
- The platform requirements when assessed at trackside can be attained from the trackside test speed through scaling with the measured train speed. I.e. measurements at 0.2m and 1.4m heights can be made at the same time and scaled as appropriate to compare with the requirement. The trackside test speed could alternatively be maximum 250 km/h to allow measurement for head pressure pulse at the same time.

A number of other points arise.

- There seems to be no reason to change the current limit values in the methodology – largely because there is no new evidence as to their adequacy or otherwise, in specifying dangerous wind speed values for different categories of passenger or trackside worker. Further work is required to specify these limits – see for example the approach outlined in [3].
- The relationship between the TSI values and these limits needs to be appreciated. It is suggested above that this might best be achieved by calculating the average number of train passes between exceedence of the limits, probably expressed in a logarithmic form for the sake of simplicity.

7. Conclusions

From the analysis of the slipstream gusts presented in the previous sections the following conclusions can be drawn.

1) There is very considerable scatter in the values of the normalised gust velocities that may be obtained from nominally identical train passes, due to the unsteady and turbulent nature of the flow.
2) In general the maximum gusts occur in the near wake of trains, but for double unit trains they can occur in the vicinity of the gap between the units and for locomotive coach combinations, maximum gusts can occur at the front of the locomotive or at the geometric discontinuity between the train and the coaches. For some configurations a significant difference between the leading and trailing position of the locomotive can be observed.
3) The magnitudes of the gust are normally distributed.
4) There is little variation of the mean normalised gust speed with vehicle speed and some increase of the run-to-run scatter with decreasing speed. However as the TSI vehicle speed restriction[1]is not difficult to meet, there seems to be little reason to change it.
5) There is some variation of gust magnitudes with wind conditions, but these can only be observed in very large datasets. Nonetheless the current TSI cross wind limit seems to be sensible in this regard and should not be changed.
6) The uncertainty on *U(TSI)* is a function of the number of train passes. For 20 train passes and a given fixed test site the standard uncertainty is of the order of 6%. A change of test site can change this figure.
7) In general the relative values of *U(TSI)* between trains are consistent with the ensemble analysis of Part 1, in particular showing high values for the trains and situations where high ensemble averages were obtained.

[1] For a valid set of measurements, conditions for train speed v_{tr} are: at least 50 % of the measurements within ± 5 % of $v_{tr,test}$ and 100 % of the measurements within ± 10 % of $v_{tr,test}$.

8) If the values of *U(TSI)* are plotted against height above the rail for both platform and trackside data, the data for any particular train tends to fall onto one curve, with very few exceptions, suggesting that platform tests may not be required in the TSI methodology.

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[1] CEN Railway applications — Aerodynamics — Part 4: Requirements and test procedures for aerodynamics on open track, CEN EN 14067-4:2005+A1, 2009

[2] EU Technical Specification for Interoperability Relating to the 'Rolling Stock' Sub-System of the Trans-European High-Speed Rail System (HS RST TSI), 2008/232/EC, 2008

[3] Jordan S, Sterling M, Baker C.J., Modelling the response of a standing person to the slipstream generated by passenger trains, Journal of Rail and Rapid Transit 223, 567- 578, 2009

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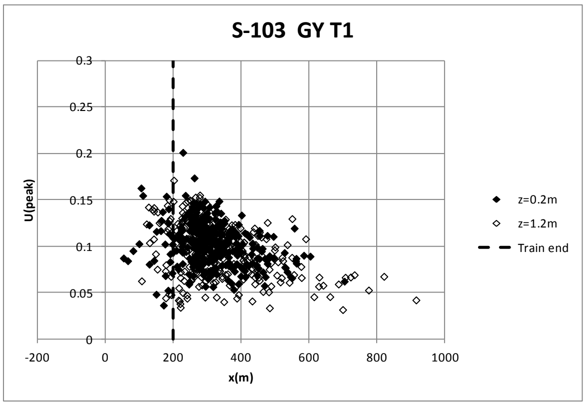


Figure 1 Gust values for S-103

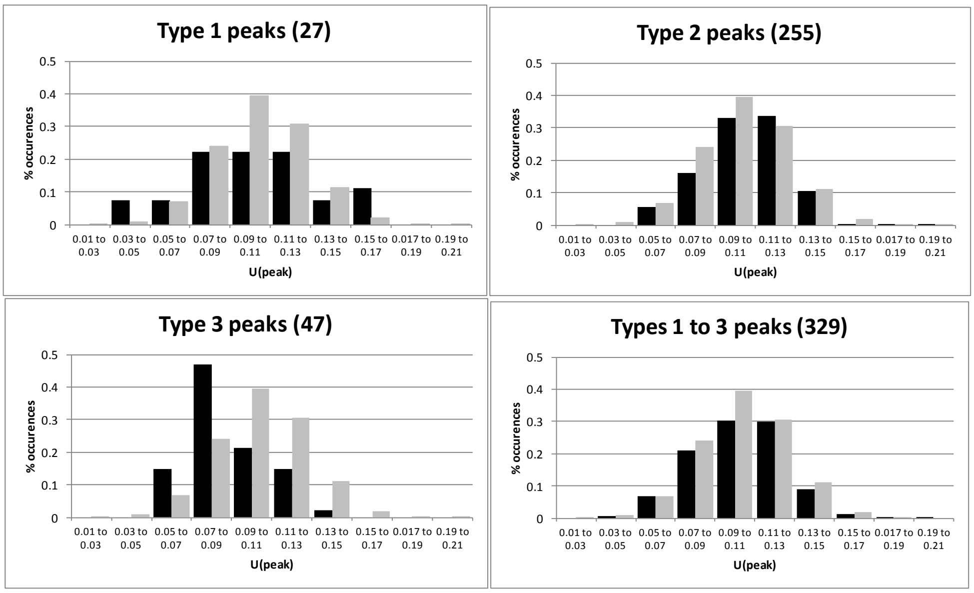


Figure 2 Frequency distributions for S103 Velaro gust magnitudes (black bars are gust values, grey bars are normal distribution with mean and standard deviation of the overall sample)

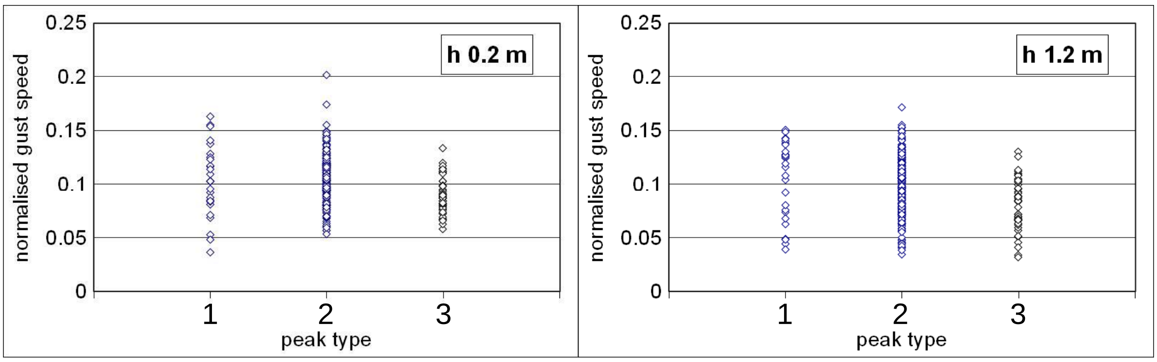


Figure 3 Partition of S103 data according to the three "types" (trainside, near wake, far wake)

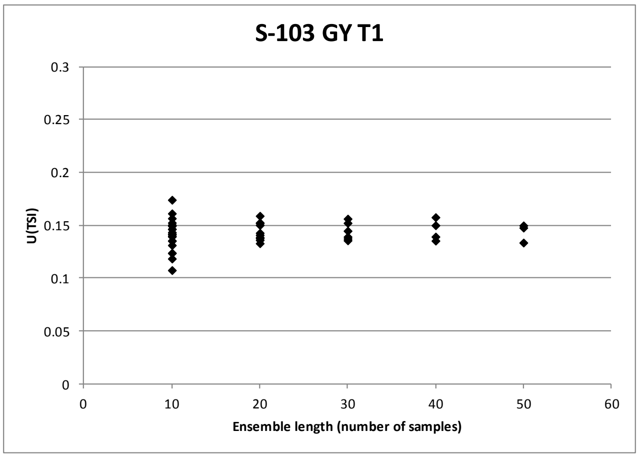


Figure 4 Effect of ensemble length on S-103 *U(TSI)* values

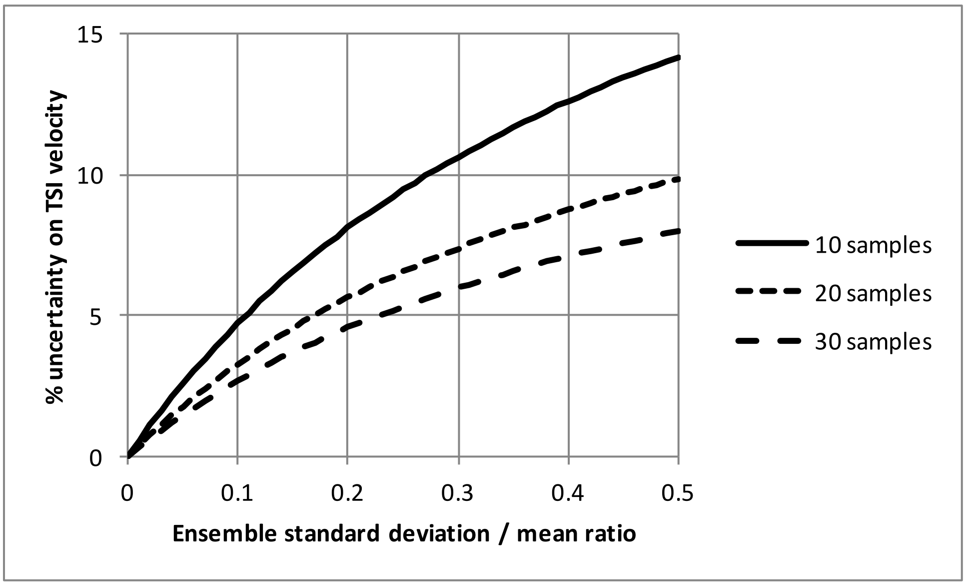


Figure 5 Variation of standard uncertainty with number of runs, assuming the test site to be fixed

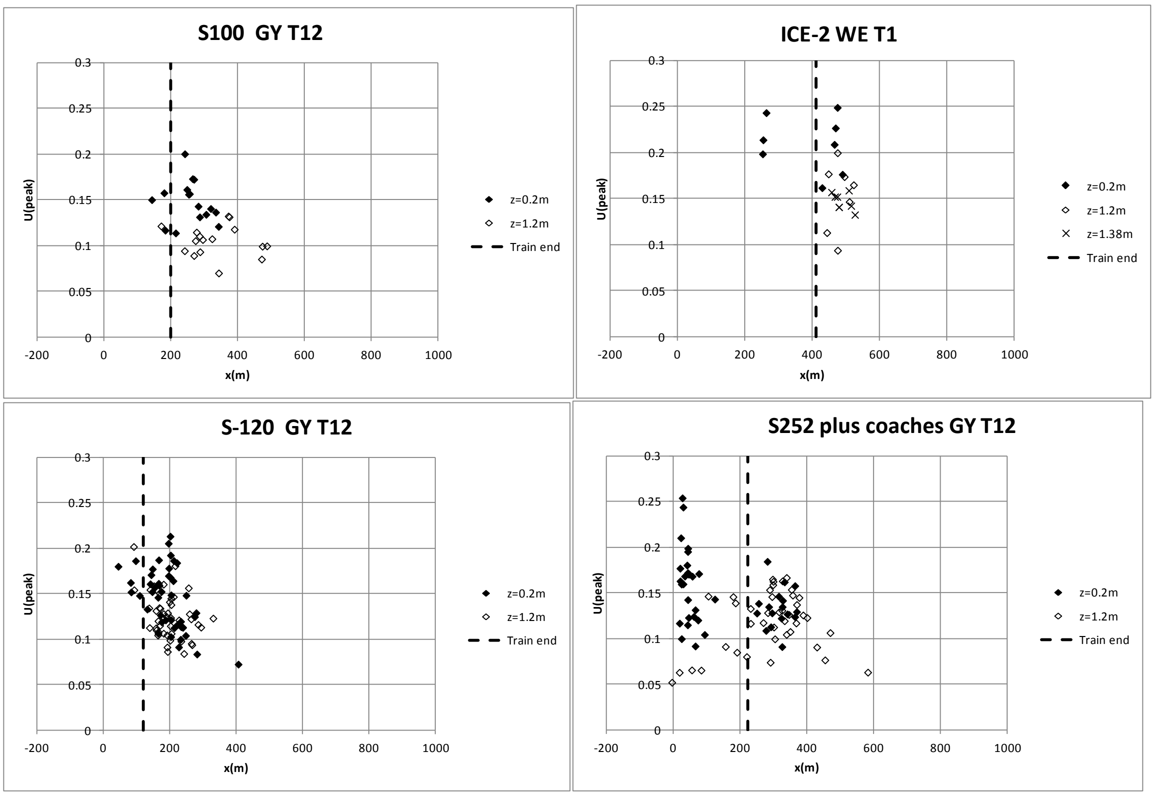


Figure 6 Gust positions and magnitudes for representative train types

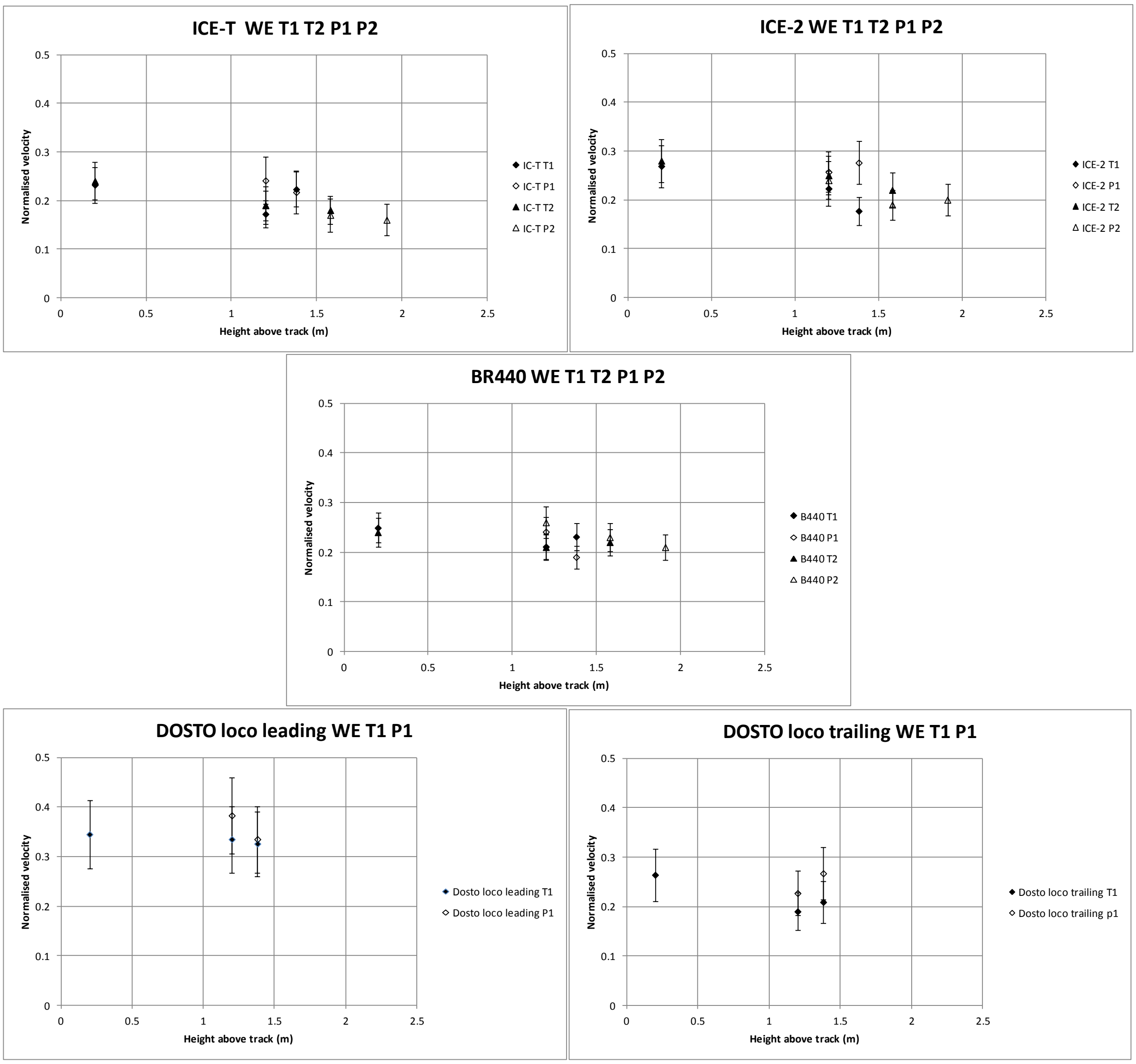


Figure 7 Comparison between *U(TSI)* values at trackside and above platforms. The error bars indicate the 95% confidence limits on the data.

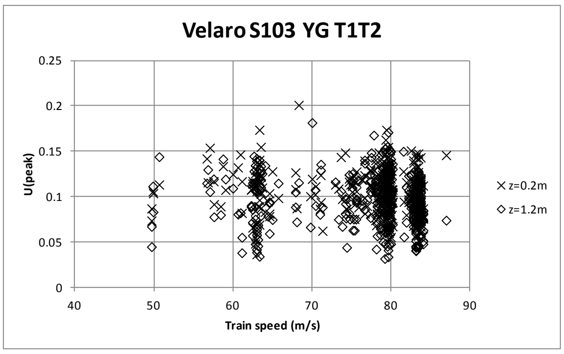
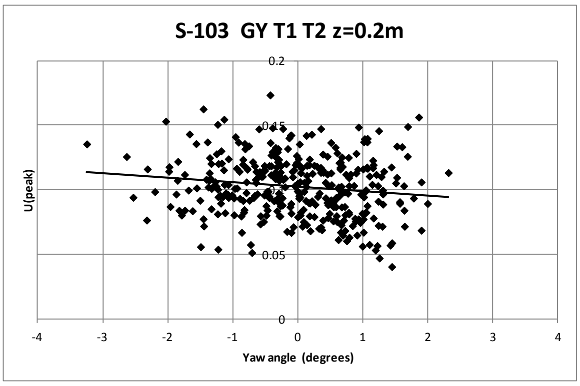


Figure 8 The effect of vehicle speed on normalised gust magnitudes for T1 and T2.



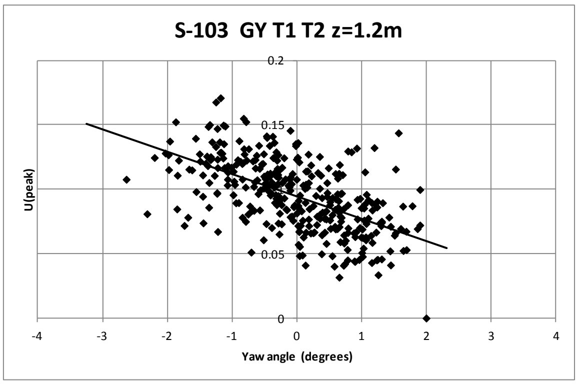
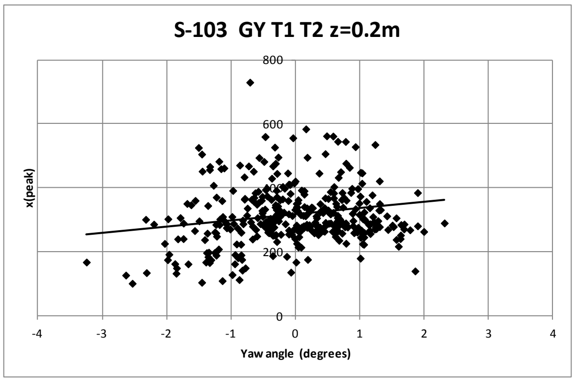


Figure 9 The effect of cross winds on gust magnitude



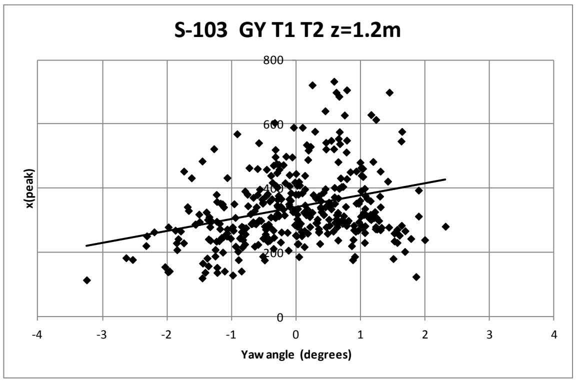


Figure 10 The effect of cross winds on gust position

Sites or dataset (Notes 1,2,3)			GY T12	GY T1	WE T1	WE T2	WE P 1	WE P2	KH P	RA T	RA P	GB T	GB P
Investigator (Note 4)			DB	BT	DB	UB	DB	UB	UB				
Anemometer heights above top of rail (m) (Notes 5,6,7,8)			0.2 1.2	0.2 1.2 1.58	0.2 1.2 1.38	0.2 1.2 1.58	1.2 1.38	1.2 1.58 1.92	0.76 1.2 1.38 1.58	0.5	1.31	0.7	1.6
Platform height (m)							0.18	0.38	0.38		0.31		0.9
Train	**Length (m)**	**Max speed (kph)**											
High speed trains, single unit													
S-100	200	300	x	x									
S-102	200	300	x	x									
S-103	200	300	x	x									
S-120	107	250	x	x									
S-130	180	250	x	x									
ICE-1	364	280							x	x	x		
ICE-2	206	280								x			
ICE-3	400	320							x				
ICE-T	184	230			x	x	x	x					
High speed trains double unit													
S-102	400	300	x	x									
S-103	400	300	x	x									
ICE-2	411	280			x	x	x	x					
Low speed multiple unit													
BR440	71	160			x	x	x	x					
Locomotives and carriages													
S-252 + coaches	222	200	x	x									
Dosto loco leading	130	140			x		x						
Dosto loco trailing	130	140			x		x						
EC101 + coaches	280	220							x				
C91 + coaches	220	225										x	x

Notes

1. Sites. GY - Guadalajara – Yebes in Spain, WE – Westendorf in Germany, KH – Kutzenhausen in Germany
2. Datasets. RA – RAPIDE database, GB – GB database
3. T1 – track 1, T2- track 2, T12 – tracks 1 and 2, P1 – platform 1, P2 – platform 2, T – trackside, P – platform
4. Investigators. DB – Deutsche Bahn, BT – Bombardier Transportation, UB – University of Birmingham
5. All anemometers, except those mentioned below, were at 3.0m from the centre of the track i.e. the TSI measurement positions.
6. 1.92m WE P2 is based on GB positions, 2.5m from the nearest track (3.25m from track centreline).
7. RA T measurements were made 2.5m from the track centre line. RA P measurements were made 1.5m from platform edge, approximately 3.0m from track centreline
8. GB T measurements were made 1.95m from nearest rail.

Table 1 The experimental sites, trains and measurement positions

Train	Speed (m/s)	GY T1 T2	GY T1	WE T1	WE T2	WE P 1	WE P2	KH P	RA T	RA P	GB T	GB P
High speed trains single units												
S-100	79-86	16	6									
S-102	75-84	20	9									
S-103	70-87	269	97									
S-120	40-71	44	21									
S-130	40-66	22	8									
ICE-1	51-69							22	9	11		
ICE-2	60-78								7			
ICE-3	45-55							22				
ICE-T	35-59			10	33	11	15					
High speed trains double units												
S-102	56-84	7										
S-103	79-84	7										
ICE-2	47-58			11	32	11	14					
Short passenger units												
BR440	35-49			19	49	20	20					
Locomotives and carriages												
S-252 + coaches	40-56	33	7									
Dosto loco leading	32-39			9		9						
Dosto loco trailing	32-28			7		7						
EC101 + coaches	44-55							32				
C91 + coaches	44-63										8	8

Table 2 Number of runs used in gust analysis

Train	z (m)	GY T12 DB	GY T1 BT	WE T1	WE T2	RA T
S-100	0.2	0.191± 0.019	0.191 ±0.030			
	1.2	0.136± 0.014	0.151 ±0.033			
	1.58		0.148 ±0.042			
S-102	0.2	0.174±0 .025	0.149 ±0.019			
	1.2	0.132 ±0.014	0.160 ±0.037			
	1.58		0.161 ±0.031			
S-103	0.2	*0.144 ±0.004*	*0.159 ±0.009*			
	1.2	0.149 ±0.006	0.162 ±0.011			
	1.58		0.178 ±0.014			
S-120	0.2	0.213 ±0.018	0.242 ±0.047			
	1.2	0.175 ±0.013	0.234 ±0.046			
	1.58		0.180 ±0.027			
S-130	0.2	0.251 ±0.029	0.237 ±0.047			
	1.2	0.190 ±0.020	0.184 ±0.031			
	1.58		0.218 ±0.060			
ICE-1	0.5					0.221 ±0.038
ICE-2	0.5					0.251 ±0.049
ICE-T	0.2			0.232 ±0.045	0.24 ±0.021	
	1.2			0.172 ±0.030	0.19 ±0.017	
	1.38			0.223 ±0.052		
	1.58				0.18 ±0.016	

Table 3 *U(TSI)* values of high speed single units at trackside (italics indicate case where confidence limit of nominally similar runs do not overlap)

Train	z (m)	GY T12 DB	WE T1	WE T2
S-102	0.2	0.226 ±0.045		
	1.2	0.162 ±0.032		
S-103	0.2	0.170 ±0.034		
	1.2	0.156 ±0.031		
ICE-2	0.2		0.269 ±0.030	0.28 ±0.025
	1.2		0.223 ±0.036	0.25 ±0.022
	1.38		0.177 ±0.017	
	1.58			0.22 ±0.019

Table 4 *U(TSI)* values of high speed double units at trackside

Train	z (m)	WE T1	WE T2
BR440	0.2	0.249 ±0.035	0.24 ±0.017
	1.2	0.211 ±0.028	0.21 ±0.015
	1.38	0.231 ±0.027	
	1.58		0.22 ±0.016

Table 5 *U(TSI)* values of short passenger unit at trackside

Train	z (m)	GY T1 T2 DB	GY T1 BT	WE T1	GB T
S-252 + coaches	0.2	0.198 ±0.017	0.232 ±0.070		
	1.2	0.182 ±0.020	0.184 ±0.054		
	1.58		0.147 ±0.034		
Dosto loco leading	0.2			0.345 ±0.038	
	1.2			0.334 ±0.047	
	1.38			0.326 ±0.052	
Dosto loco trailing	0.2			0.264 ±0.054	
	1.2			0.190 ±0.037	
	1.38			0.209 ±0.041	
C91 + coaches	0.7				0.305 ±0.056

Table 6 *U(TSI)* values of locomotive plus coach combinations at trackside

Train	z (m)	WE P1	WE P2	KH P	RA P
ICE-1	0.76			0.22 ±0.024	
	1.2			0.20 ±0.021	
	1.31				0.205 ±0.032
	1.38			0.16 ±0.017	
	1.58			0.17 ±0.018	
ICE-3	0.76			0.25 ±0.027	
	1.2			0.20 ±0.021	
	1.38			0.19 ±0.020	
	1.58			0.19 ±0.020	
ICE-T	1.2	0.241 ±0.033	0.19 ±0.026		
	1.38	0.217 ±0.028			
	1.58		0.17 ±0.023		
	1.92		0.16 ±0.022		

Table 7 *U(TSI)* values above platforms for high speed single units

Train	z (m)	WE P1	WE P2
ICE-2	1.2	0.257 ±0.026	0.24 ±0.033
	1.38	0.276 ±0.037	
	1.58		0.19 ±0.026
	1.92		0.20 ±0.027

Table 8 *U(TSI)* values above platforms for high speed double units

Train	z (m)	WE P1	WE P2
BR440	1.2	0.241 ±0.025	0.26 ±0.029
	1.38	0.19 ±0.021	
	1.58		0.23 ±0.026
	1.92		0.21 ±0.024

Table 9 *U(TSI)* values above platforms for short passenger units

Train	z (m)	WE P1	K P	GB P
Dosto loco leading	1.2	0.383 ±0.055		
	1.38	0.335 ±0.043		
Dosto loco trailing	1.2	0.227 ±0.036		
	1.38	0.267 ±0.059		
EC101 plus coaches	0.76		0.31 ±0.027	
	1.2		0.27 ±0.024	
	1.38		0.23 ±0.020	
	1.58		0.23 ±0.020	
Class 90 plus coaches	1.60			0.233 ±0.043

Table 10 *U(TSI)* values above platforms for coach and carriage combinations

	Conventional *U(TSI)* / Ensemble *U(TSI)*	
	z=0.2m	z=1.2m
S-100	0.82	0.85
S-102	0.95	0.77
S-103	0.88	0.94
S-120	0.96	0.96
S-130	1.09	0.95
S-252	0.95	1.08

Table 11 Comparison of *U(TSI)* values calculated using the one second moving average ensemble mean and using the conventional methodology. Ratios below unity indicate the conventional methodology based on gusts gives lower values than a methodology based on ensembles.

		Normalised mean	Normalised sd	Max speed m/s	Mean m/s	Stan. Dev. m/s	*U(TSI)* m/s	Relevant limit m/s	log (return passes)
S-100	z=0.2m	0.148	0.023	83.3	12.3	1.9	16.1	22	6.7
S-102	z=0.2m	0.112	0.030	83.3	9.3	2.5	14.4	22	6.6
S-103	z=0.2m	0.102	0.021	83.3	8.5	1.7	12.0	22	14.5
S-120	z=0.2m	0.145	0.034	69.4	10.1	2.4	14.8	22	6.7
S-130	z=0.2m	0.173	0.039	69.4	12.0	2.7	17.5	22	3.9
S-252	z=0.2m	0.142	0.028	55.6	7.9	1.6	11	20	14.5
BR440 T	z=0.2m	0.162	0.043	44.4	7.2	1.9	11	20	11
DOSTO LL T	z=0.2m	0.281	0.032	44.4	12.5	1.4	15.3	20	7.2

Table 12 Calculation of probability of limit values being exceeded.

s